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Unified Gas-Kinetic Wave-Particle Methods VI: Disperse Dilute Gas-Particle Multiphase Flow

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Abstract. A coupled gas-kinetic scheme (GKS) and unified gas-kinetic wave-particle (UGKWP) method for the disperse dilute gas-particle multiphase flow is proposed. In the two-phase flow, the gas phase is always in the hydrodynamic regime and is followed by GKS for the Navier-Stokes solution. The particle phase is solved by UGKWP in all regimes from particle trajectory crossing to the hydrodynamic wave interaction with the variation of particle's Knudsen number. In the intensive particle collision regime, the UGKWP gives a hydrodynamic wave representation for the particle phase and the GKS-UGKWP for the two-phase flow reduces to the two-fluid Eulerian-Eulerian (EE) model. In the rarefied regime, the UGKWP tracks individual particle and the GKS-UGKWP goes back to the Eulerian-Lagrangian (EL) formulation. In the transition regime for the solid particle, the GKS-UGKWP takes an optimal choice for the wave and particle decomposition for the solid particle phase and connects the EE and EL methods seamlessly. The GKS-UGKWP method will be tested in all flow regimes with a large variation of Knudsen number for the solid particle transport and Stokes number for the two-phase interaction. It is confirmed that GKS-UGKWP is an efficient and accurate multiscale method for the gas-particle two-phase flow.

AMS subject classifications: 65M08, 76T15, 76P05, 82B40

Key words: Unified gas-kinetic wave-particle method, gas-kinetic scheme, disperse gas-particle two-phase flow.

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1 Introduction

Gas-particle flow is a common two-phase system and it appears in both natural phenomena and engineering industries, such as volcanic eruption, sandstorm propagation, chemical transport, and combustion process, etc [3, 11, 18, 40]. Numerical simulations become powerful and indispensable tools for the study of gas-particle system due to the complex physics and difficulties in the experiments and theoretical analysis. Therefore, the development of reliable, accurate, and efficient numerical algorithm to study the multiscale transport associated with different flow regimes is highly demanding in both scientific research and engineering application.

The flow physics of the gas-particle system is very complicated due to particle-particle collision and particle-gas interaction. While the gas phase is in continuum flow regime and modeled by the Navier-Stokes equations, the particle phase can cover a wide range of flow regimes with multiscale transport mechanism [29, 40, 54]. The simulation of gas-particle flow has to include the gas-particle interaction and particle-particle collision. The flow physics is mainly controlled by two non-dimensional parameters, Stokes number St and Knudsen number Kn_s [40]. The Stokes number is related to the drag force on the particle exerted by the surrounding gas flow, which accounts for the momentum exchange between gas and solid particle phase. The dusty flow model is an example in the continuum flow regime when the Stokes number can be very small [46, 49]. Besides, the heat conduction between the gas and solid particle leads to the energy exchange.

Another important parameter is the Knudsen number, characterizing the flow regime of particle phase. At small Knudsen number, the intensive particle-particle collision drives the particle phase to a local equilibrium state and evolves as a continuum flow. Then, the Eulerian-Eulerian (EE) model is usually employed for the gas-particle system under the Eulerian framework, and the EE model is also called two fluid model (TFM). Many studies have been conducted using TFM [2, 22, 46, 50]. The kinetic theory-based granular flow (KTGF) is one representative method of TFM. Based on the analogy between the solid particle behavior in a granular flow and the molecule movement, the kinetic theory is used to get the granular flow equations [8,23,38], which is further extended to the disperse gas-particle system [14, 65]. Since the particle size is large in granular flow, the particle-particle collision should be inelastic, which distinguishes the dynamics of solid particles and molecules [38]. The limitation of TFM is that it cannot describe the non-equilibrium state under the quasi-equilibrium assumption [3]. A representative non-equilibrium phenomenon of disperse phase is the particle trajectory crossing (PTC), which occurs in the extremely dilute flow regime with a large Knudsen number [40]. The TFM fails to capture the PTC transport [16]. The TFM is mostly applicable in the fluid dynamic regime for both gas and particle phase [40].

On the other hand, when the Knudsen number is not very small, the local equilibrium assumption for disperse phase is no longer satisfied. Therefore, both the transport and collision processes have to be considered for the particle phase movement. Under such a non-equilibrium flow regime, the Eulerian-Lagrangian (EL) model is usually adopted.